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History of the solar ponds: A review study

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ABSTRACT

Solar pond was discovered as a natural phenomena around the turn of the last century in the Medve Lake in Transylvania in Hungary. In this lake, temperatures up to 70 °C were recorded at a depth of 1.32 m at the end of the summer season. The minimal temperature was 26 °C during early spring. The bottom of this lake had a salt NaCl with concentration of 26 percent. Solar pond is artificially constructed. To prevent convection, salt water is used in the pond. Those ponds are called "salt gradient solar pond". Nowadays, mini solar ponds are also being constructed for various thermal applications. It was concluded that the optimum value of salinity in the mini solar pond is 80 g/kg of water.

Contents

1. Introduction

The Solar pond is a body of water that collects and stores solar energy. Anderson [1] reported a similar lake in Oroville (Washington State) where a temperature of 50 °C at a depth of 2 m was observed in the summer season. This phenomena has been observed and reported also by Wilson and Wellman [2], Hoare [3], Por [4], Melack and Kilham [5], Hudica and Sonnefeld [6] and Cohen et al. [7].

In this paper, various designs of solar pond have been discussed. The factors affecting the thermal performance of the solar ponds, mode of heat extraction and its applications are reviewed.

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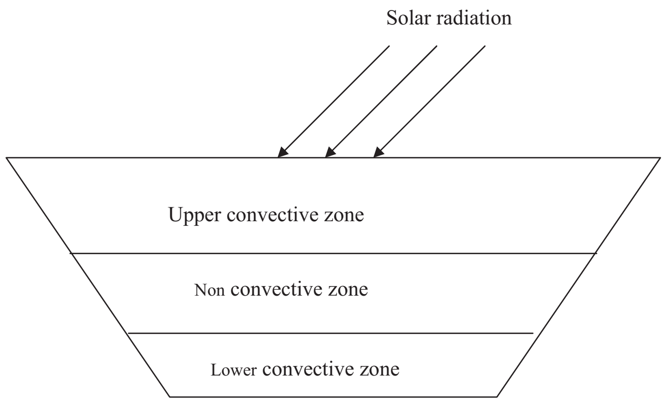

Fig. 1. Diagram of the salt gradient solar pond.

2. Types of solar ponds

There are several types of solar ponds such as salt gradient solar ponds, partitioned solar ponds, viscosity stabilized solar ponds, membrane stratified solar ponds, saturated solar ponds, membrane viscosity stabilized solar ponds, and shallow solar ponds. These types will be discussed briefly in the following sections.

2.1. Salt gradient solar pond (SGSP)

The salt gradient solar pond is typically 1–2 m deep and the bottom is painted black as shown in Fig. 1. The convection currents that normally develop due to the presence of hot water at the bottom and cold water at the top are prevented by the presence of strong density gradient from bottom to top. This density gradient is obtained by using a high concentration of suitable salts such as NaCl at the bottom of the pond and negligible concentration at the top. The thermal conductivity of the salt solution, which is even less than that of stagnant water, decreases with the increase of salinity and thus acts as an insulating layer [8].

The salt gradient solar pond is described to be consisting of three layers. The top surface layer is known as the convection zone that is a zone of constant temperature and salinity. The thickness of this surface layer varies from 0.1 to 0.4 m and is formed due to upward salt transport, surface heating and cooling and wave-action. The second layer is the nonconvective zone (NCZ) with thickness ranges from 0.6 to 1.0 m, which acts as an insulating layer of the pond. The density in the NCZ increases with increasing depth of the gradient layer. The thickness of the gradient layer depends on the desired temperature, solar transmission properties and thermal conductance of water. The bottom or the third layer is a high temperature layer known as the storage layer or the storage zone. This layer has a constant temperature and salinity. Useful heat is usually extracted from this layer; its thickness depends on the temperature and the amount of the thermal energy to be stored [8].

In 1948, Block suggested the adoption of a density gradient to eliminate the convection in the solar pond. During the fifties of the last century, an extensive pioneering investigation was initiated by Tabor et al. [9–12]. They have conducted research on several small ponds and they have recorded temperatures as high as 103 °C in small ponds with collection efficiencies of the order of 15 percent. Theoretical and experimental observations on the laboratory scale solar ponds for understanding the physics of the solar pond were carried out by Weinberger [13], Elata and Lavin [14], Tabor and Matz [15] and Hirschmann [16]. Stolzenbach et al. [17] have developed numerical methods to predict temperature distributions within the solar pond. Some theoretical investigations on solar ponds have been carried out by Usmanov et al. [18,19].

In order to improve the performance of the conventional salt gradient solar pond (CSGSP), the concept of the advanced solar pond (ASP) was introduced by Osdor [20]. There are two main features that distinguish the ASP in comparison with the CSGSP: (i) the overall salinity of the pond is increased, and (ii) an additional (stratified) flowing layer is established in the lower part of the gradient zone (GZ). Increased salinity is proposed primarily for the surface layer in order to reduce evaporative heat loss; however, this requires the salinity in the rest of the pond to be increased as well. In order to maintain stability, the stratified flowing layer is used for additional heat extraction, similar to the flow that would be established in the lower convective zone (LCZ) for the same purpose. Therefore, heat is extracted over a larger depth of the pond and heat is also recovered which might otherwise have been conducted upward out of the LCZ [21].

A suitable salt used in the solar ponds must meet the following characteristics [8]; it must have a high value of solubility to allow high solution densities, the solubility should not vary appreciably with temperature, its solution must be adequately transparent to solar radiation, it must be environmentally benign and safe to handle and it must be available abundance near site; so that its total delivered cost is low. The heat extraction from the salinity gradient solar ponds using heat pipe heat exchangers had been investigated [22]. It was found that, there was a drop in temperature of lower convective zone from 40 °C to 39 °C in 3 h period of heat extraction. Using mini solar ponds for preheating saline water of solar stills had been studied [23–25]. It was concluded that the optimum value of salinity in the mini solar pond is 80 g/kg of water. Ould Dah et al. [26] studied the influence of heat extraction on the performance and stability of a mini solar pond. It was concluded that the mini pond efficiency could be improved considerably by extracting the heat from the non-convective zone instead of the conventional method of heat extraction from the lower convective zone. However, this method of heat extraction reduces the stability of the lower interface.

2.1.1. Establishment and maintenance of salt gradient

The salt concentration gradient in the pond can be generated by various methods dependent on local requirement [27]. These methods include natural diffusion, stacking, redistribution and falling. In the natural diffusion method, the upper half is filled with water, top and bottom concentrations are maintained constant by regularly washing the surface and adding salt in the bottom. Owing to the upward diffusion of salt, a salinity gradient will be established. This is a very slow method of establishing the salt gradient and should be considered if the pond is very large, or if the starting time could be unlimited [28].

Stacking involves the filling of the pond with a storage layer of high concentration solution and several other layers of salt solutions of differing concentration. The concentration of salt in successive layers is changed in steps from near saturation at the bottom to fresh water at the top. For a typical pond of about 1 m depth, one might use about 10 layers. The turbulent mixing generated during filling and continuous molecular diffusion modifies the stepwise type concentration profile into a nearly linear concentration profile [29,30]. The practical approach for stacking used in most solar ponds is that the bottom layer is filled first and successively lighter layers are floated upon the lower denser layers. However, some experimental ponds in Australia [31,32] have been built by injecting in the bottom successively denser layers which lifted the lighter layers filled previously.

Redistribution is considered to be the most convenient for larger ponds [33,34], when fresh water is injected at some level into homogeneous brine, it stirs and uniformly dilutes the brine from a few centimeters below the injection level to the surface. Hence, the artificial pond is filled with high salinity brine to half of its total

depth and then fresh water is added through a diffuser. Initially, the diffuser is placed at the bottom and the water is added in the pond, flowing in as under current and the level in the pond increases. The diffuser is moved upward continuously or in steps. Timing of the movement is so adjusted that the diffuser as well as the water surface reaches the final level at same time. At the completion of this process we have a nearly uniform salt concentration gradient in the pond [28].

The salt gradient can also be maintained by periodically adding of a saturated salt solution at the bottom and washing the surface with fresh water [35]. A more efficient approach, which does not require the continual addition of salt, is the falling pond concept [36,37], wherein, hot brine is withdrawn from the bottom layer without causing disturbance to the layer above. This is possible, since in a fluid system stratified with a density gradient, selective flow of the bottom layer can be accomplished without requiring a mechanical separation between the flowing and stable regions of the system [38–40]. The hot brine withdrawn from the solar pond is passed through the flash evaporator to remove some of its water. The solution now having a high concentration and smaller volume is reinjected in the pond bottom and the removed water is replaced into the surface layer, consequently, the concentration gradient would be maintained. The fall in surface level due to evaporation is also restored by the addition of fresh water to keep both the pond depth and the surface concentration constant. In this process, the gradient tends to be displaced downwards.

It is acute that the brine circulation rate and the location of the suction diffuser with respect to the lower interface must be selected carefully in such a manner that withdrawal and ri-injection of brine does not disturb the salinity gradient [41].

2.1.2. The stability of the pond

The stability of solar ponds has been extensively studied by Huppert and Moore [42], Lashuk et al. [43], Zangrando [28,44], and Sundaram [45]. The density of liquid in the solar pond depends on, the salt concentration (C) and temperature (T) of the liquid. Weinberger [13] indicated that there will be no vertical thermal convection or the pond will be stable when the density gradient on account of the salt concentration gradient is greater than the negative density gradient produced by the temperature gradient (or the total derivative of density with respect to depth) is greater than or equal to zero, [8] i.e.:

$$\frac{d\rho}{dX} = \frac{\partial\rho}{\partial C}\cdot\frac{\partial C}{\partial X} \geq -\frac{\partial\rho}{\partial T}\cdot\frac{\partial T}{\partial X} \tag{1}$$

where ρ is the density of the liquid and X is the depth of the water (measured positive going downward).

2.2. Partitioned solar pond (PSP)

Tabor [10] has reported the following problems that occurred during the operation of solar pond: (i) biological growth of algae and bacteria, (ii) dirt falling into the pond and decreasing its transparency. (iii) Evaporation causing too high concentration at the top and (iv) disturbance of the concentration gradient while extracting heat. Adding chemicals can prevent biological growth [46]. The other problems may be overcomed by installing two transparent partitions one on top or few centimeters blow the surface of the pond and the other at a depth of 1–2 m. A thin water layer above the top partition brings both advantages and disadvantages. The disadvantages, especially in windy locations, include evaporative cooling and increased reflectivity due to wave action. On the positive side, there is a decrease in reflective losses because the water has a lower index of refraction than plastics, so that reflective losses at a water-plastics boundary are small. The lower partition separates the insulating layer from the convective layer. It improves the stability of the pond and facilitates the extraction of heat. Instabilities due to buoyancy can be avoided either by making the lower partition stiff (e.g. glass panes) or if a flexible partition (e.g., a Tedlar sheet) is used, by filling the convection zone with salt water. To improve convection, heat is extracted just below the partition either by removing hot water or brine directly or by running fresh water through a network of heat exchanging plastic pipes. The Tedlar may be preferable if brine is used in the convective zone [46].

2.3. Viscosity stabilized solar pond (VSSP)

Nonconvective layers of solar ponds are ordinarily composed of salt gradient layers. Salt gradient solar ponds, however, have a number of difficulties, they may cause environmental pollution in the event of a salt leakage and the salt gradient layer needs frequent maintenance. In order to eliminate these problems, Shaffer [47] proposed a new type of solar ponds using a transparent polymer gel as a nonconvecting layer. The polymer gel has low thermal conductivity and is used at a near solid state; so that it will not convect [48].

Materials suitable for viscosity stabilized solar ponds should have high transmittance for solar radiation, high efficiency of the chosen thickness and should be capable of performing at temperatures up to 60 °C. Polymers such as gum Arabic, Locust bean gum, Starch and Gelatin are all potentially useful materials. The ideas of viscosity stabilized solar pond appears to be promising but presently is not economically competitive salt gradient solar pond [8]

2.4. Membrane stratified solar pond (MSSP)

Membrane stratified solar pond is a type of nonsalt solar ponds, which is a body of liquid utilizing closely spaced transparent membranes. The membrane space for suppressing convection, should be very small and a large number of high transparent films are required [48]. The buoyancy effect is balanced by the weight of water so that solar radiation is converted into sensible heat [49]. Three types of membranes are suggested for the membrane stratified solar pond, which are [50] horizontal sheets, vertical tubes, and vertical sheets.

2.5. Saturated solar pond (STSP)

The problems of maintenance density in the conventional salt gradient solar pond (CSGSP) can be overcomed by making the pond saturated at all levels, with a salt whose solubility increases with temperature. Such saturated ponds have no apparent diffusion problems and the gradients are self-sustaining depending on local temperature; thus the main advantage of such a pond is its inherent stability. In such a pond, vertical diffusion of salt is prevented and the density gradient is stable; thus making the pond maintenance free [51]. Salt gradient solar ponds have advantages for long-term energy storage. In contrast, nonsalt solar ponds such as membrane stratified ponds and shallow solar ponds, are more suitable for short-term energy storage because the temperature rise of the pond water is rapid. The performance of these nonsalt solar ponds was established by field tests, and reference data for design of these solar ponds were obtained from the results of the experiments and analysis [52].

2.6. Shallow solar pond (SSP)

The shallow solar pond (SSP) is a solar energy collector that is intended to supply large amounts of heat for industrial applications at a cost that is competitive with fossil fuels. Its use for the conversion of solar energy into low-grade thermal energy has been a

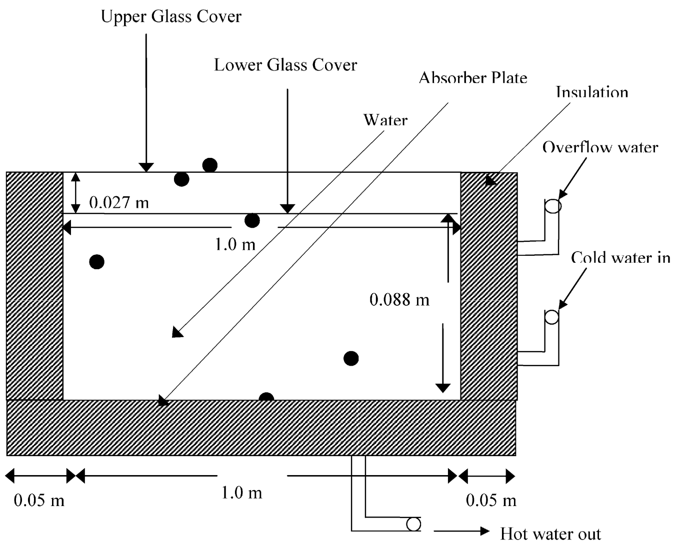

Fig. 2. Shallow solar pond with double glass cover; (●) thermocouple positions.

subject of intensive investigations for a number of years, especially by the solar energy group at Lawrence Livermore Laboratory (USA) [53]. The term shallow solar pond has much been derived from that of the solar still. The name implies that the depth of water in the SSP is very small, typically only a few centimeters, which is like a conventional solar still consisting of a blackened tray holding some water in it. The still takes advantage of evaporation of salt water by solar heat. In the SSP that shallow level is covered by means of a plastic film, in such a way that the film is in contact with the top surface of the water, and thus prevents the cooling effect due to evaporation. It is capable of heating a large quantity of water to appreciable temperature, and because of its simplicity in working, it holds out promise for one of the cheapest known methods for harnessing solar energy. A shallow solar pond is essentially a large water bag or pillow placed within an enclosure with a clear upper glazing. Water is placed within the bag, which is generally constructed from clear upper plastic film and a black lower plastic film. The depth of the water within the bag is normally in the range of 4–15 cm. The solar energy collection efficiency is directly proportional to water depth, whereas, the water temperature is inversely proportional to water depth. Solar energy is converted to thermal energy by heating the water during the day. The water is withdrawn from the SSP before sunset (or more precisely when the collection efficiency approach zero) for utilization or storage [54] (Fig. 2).

The idea of using such a simple device, viz, a water pillow for solar energy collection is not new. The Japanese have been using numerous variations of this idea to heat water for domestic usage since the thirties of the last century. Sodha et al. [55] fabricated a SSP system using PVC films in the form of a bag. The special feature of the system is the use of two transparent foils separated by a honeycomb structure. In the SSP, the black bottom of the pond absorbs the sun's rays; as a result, the water gets heated. The total solar energy absorbed by the whole system cannot be used as useful energy. This is because of several loss factors and a number of other mechanisms that reduce the total input of solar radiation. For instance, the absorbitivity of the absorbing surface of the collector is not unity. The transparent sheet over the SSP also does not allow all the radiation to get inside. There are losses due to conduction, convection, and radiation. Using a suitable insulation material reduces conduction loss. In order to reduce the thermal loss by convection and radiation, one or two transparent sheets are used over the pond [54]. Gopffarth et al. [56] have studied the performance of a horizontal plastic solar water heater. It consisted of a polyethylene water bag with a clear top and black bottom placed within a Styrofoam box and covered with Tedlar attached to a wooden frame. These designs could be improved by equipping the solar collector with a thermally insulated cover which would also function as an insulating reflector during the heat collection period. The rate of solar energy collection would be increased by means of the reflector redirecting the rays onto the collector surface. At the termination of the solar energy collection period, the cover is closed providing the unit with a means of overnight storage [57].

To improve thermal performance of the SSP, it is necessary to reduce heat losses from the upper surface of the pond. A promising approach for meeting this requirement is to introduce a semitransparent, multilayer insulation system on the upper surface of the SSP, which has been previously recognized to be effective in reducing heat losses from flat-plate solar collectors [58] and convecting solar ponds [59,60]. Kamiuto and Oda [61] have found that, as the number of surface-insulation layers is increased, the radiation-collection performance deteriorates while the heat-storage performance is improved. They found also that the optimum number of surface-insulation layers depends on the time when the water within the solar tank is removed. As this time is delayed, the number of surface-insulation layers must be increased in order to keep the water temperature high. Due to the manual handling of the insulation, it was observed that no good contact between the insulation and the glass cover was maintained. Due to this fact, Rani [62], Van Straaten [63], have suggested the introduction of a baffle plate inside the system. Tiwari and Dhiman [64] analyzed the system by incorporating the effect of the change in vent area of the baffle plate, as well as the ratio of upper and lower masses. Tiwari et al. [65] have suggested the SSP water heater with baffle plate in inclined position. This method eliminates the need for a strong and rigid baffle plate. It leads to considerable simplification in design as well as low cost in construction. Ali [66] has concluded that the change of the gap spacing between the upper film of the water bag and the glazing of the SSP does not significantly improve the performance of the SSP. By applying a circular cylindrical reflector to the shallow solar pond-electricity generating system, the annual electrical production can be increased by 40 percent [67]. Kishore et al. [68] have investigated the SSP systems with continuous heat extraction. Thermal performance of the SSP under the batch and open cycle modes of heat extraction had been studied [69,70]. Effect of using the shallow solar pond for preheating of the basin water on the thermal performance of a single-basin solar still was investigated [71]. It was found that the annual average values of the daily productivity and efficiency of the still with the SSP were found to be higher than those obtained without the SSP by 52.36% and 43.80%, respectively. Spyridonos et al. [72] studied the thermal storage efficiency for the solar saltless water ponds. They carried out a comparative study between two types of solar ponds. The first type had its surface covered by a thin layer of transparent paraffin oil. The second type was covered by transparent glass floating devices. They concluded that the first type of solar pond could be used just after the sunset of the same day, while the second to be used after one or more days of heat storage. Thermal performance of shallow solar pond integrated with a baffle plate was performed [73]. It was found that: (i) the performance of the shallow solar pond with the baffle plate is better than that without the plate, (ii) the best values of the daily efficiency are considerably higher than those reported in the literature for shallow solar ponds and built-in storage solar water-heaters. Experimental testing of the SSP with continuous heat extraction had been carried out by Ramadan et al. [74]. They concluded that, the thermal performance of the SSP under the open cycle mode is better than that under the batch mode.

Table 1
The coefficients of the water transmittance of Eqs. (4) and (5).

i	ψ	μm^{-1}	Wavelength range (μm)
1	0.237	0.032	0.2–0.6
2	0.193	0.45	0.6–0.75
3	0.167	3.0	0.75–0.9
4	0.179	35.0	0.9–1.2
5	0.224	225.0	Over 1.2

2.6.1. Modes of operation

There are three modes of heat extraction from the shallow solar pond SSP, which includes; batch, closed and open cycle continuous flow heating. In batch mode heating, ponds are filled to depth (X_w) in early morning with water at temperature (T_i). In the afternoon, when the water temperature reaches its maximum value, the pond is emptied into an insulated storage reservoir. In the closed cycle continuous flow heating, the water is continuously circulated at a constant rate between the pond and the storage reservoir in which the heat may or may not be continuously removed by an appropriate heat exchanger. In the afternoon, when the useful heat added to the pond reaches zero, all water is emptied into the reservoir. In the open cycle continuous flow heating, the cold water at initial temperature is flowed continuously at a constant rate through the pond and then taken either to storage or to some end use. As in the closed cycle mode, water is drained from pond when useful heat added to the pond reaches zero [54].

2.6.2. Transmission and absorption of radiation in the pond

It is recognized that transmission and absorption of radiation in water depends on many factors including, the incident angle of the rays, the spectral composition of radiation, reflection and diffusion from the water surface and the bottom, multiple scattering by water molecules, impurities, etc. [8]. The salts present in the pond do not appear to affect the attenuation in the pond [75]. Part of the radiation reaching the surface of the pond will be reflected and the remainder will penetrate, the radiation penetrating the surface suffers further attenuation by absorption in the pond and only a fraction reaches the bottom. The absorption is partly due to the natural absorptivity of the solution and partly to that of suspended particle [13]. The short wavelength portion of the solar radiation spectrum penetrates meters and tens of meters while the near infrared is absorbed within the first few centimeters. Water is partially opaque for infrared. Almanza and Lara [76] had adopted an experimental transmittance function in the form

$$\tau'(X) = 0.159 - 0.172 \ln\left(\frac{X_w}{X_0}\right) \qquad (2)$$

where X_w is the water depth in meters and $X_0 = 1.0$ m to make it dimensionless. With the restriction;

$$0.02\,\text{m} < X_w < 2.5\,\text{m}$$

Another formula was presented by Chepurniy and Savage as [29]

$$\tau'(X) = 0.7239 \exp(-2.081X_w) \qquad (3)$$

A more complicated function was proposed by Rabl and Nielsen [46]. They found that, the following superposition of four exponentials gave a good approximation for the pond transmittance (to within 3%, leading to an uncertainly of few degrees in the water temperature) (Table 1)

$$\tau'(X) = \sum_{i=1}^{4} \psi_i \exp(-\mu_i X_w) \qquad (4)$$

where μ_i is the extinction coefficient of the solar radiation portion ψ_i. Another similar function was proposed by Sodha et al. [77] to give more accuracy as follows:

$$\tau'(X) = \sum_{i=1}^{5} \psi_i \exp(-\mu_i X_w) \qquad (5)$$

3. Energy extraction from solar ponds

There are two methods of extracting heat from the lower convective zone of the solar pond. The first, which is the most commonly suggested method, is to extract the bottom layer of heated brine by using appropriate diffuser to prevent excessive velocities of motion within the pond and thereby minimize the erosion of the gradient zone. The heat of the heated brine is removed by an external heat exchanger and the cooled brine is returned to the pond on the other end [40]. The second method involves a heat exchanger that is placed in the lower convective zone of the pond [78]. Its most appropriate position is just below the gradient zone, so that the heat removal can stimulate convection throughout the lower convective zone and remove heat from its entire volume. This method of heat extraction has several disadvantages. These disadvantages include large quantity of tubes are required, difficulties in locating the heat exchanger, difficult to repair, corrosion problems, etc. [8].

The amount of useful energy extracted from the solar pond depends on the design of the pond as well as on the energy collected in the storage zone of the salt gradient solar pond (SGSP). The ratio of the amount of extracted heat from the SGSP to the total solar insolation reaching the upper surface of the pond is referring to as the thermal efficiency of the pond [79]. These methods of heat extraction are also applicable for the other types of solar ponds.

4. Applications of solar ponds

Because of large storage of heat and negligible diurnal fluctuation in pond temperature, solar pond has variety of applications like, heating and cooling of buildings, swimming pool and greenhouse heating, industrial process heat, desalination, power production, agricultural crop drying, etc.

4.1. Heating of buildings

Because of the large heat storage capability in the lower convective zone (LCZ) of the solar pond, it has ideal use for house heating even for several cloudy days [8]. The solar pond may be operated in conjunction with a heat pump. The heat pump could serve as an air conditioner in summer, the fresh water layer above the top partition (in partitioned solar pond) could be designed to serve as a heat sink to increase the coefficient of performance of air conditioner [79].

4.2. Power production

The concept of solar pond for power production holds great promise in those areas where there is sufficient insolation and soil conditions allow for construction and operation of large area solar ponds. These ponds can be used for generating meaningful quantities of electrical energy. An even low temperature that is obtained from solar pond can be converted into electrical power. The conversion efficiency is limited due to its low operating temperature (70–100 °C). Because of low temperature, the solar pond power plant requires organic working fluids that have low boiling points such as Halocarbones (such as Freon) or Hydrocarbones (such as Propane) [8].

4.3. Industrial process heating

In industrial process heating, the thermal energy used directly in the preparation and/or treatment of materials and goods manufactured by industry. The solar pond can play a significant role in supplying the process heat to industries, thereby, saving oil, natural gas, electricity, and coal [8].

4.4. Desalination

Multi-flash desalination units along with a solar pond is an attractive proposition for getting distilled water because the multi-flash desalination plant works below 100 °C which can be achieved by a solar pond. This system will be suitable at places where potable water is in short supply and brackish water is available. It has been estimated that about 4700 m^3/day distilled water can be obtained from a pond of 0.31 km^2 area with a multi-effect distillation unit. Moreover, this desalination plant [8].

5. Conclusions

On the basis of the solar pond review, the following conclusions can be drawn:

(i) The temperature, salinity and density of UCZ and LCZ are almost constant. Whereas, in NCZ they are increasing with depth.
(ii) Nonsalt solar ponds such as membrane stratified ponds and shallow solar ponds, are more suitable for short-term energy storage because the temperature rise of the pond water is rapid.
(iii) The annual average values of the daily productivity and efficiency of the still with the shallow solar pond were found to be higher than those obtained without the SSP by 52.36% and 43.80%, respectively.
(iv) The number of surface-insulation layers is increased, the radiation-collection performance deteriorates while the heat-storage performance is improved.
(v) The change of the gap spacing between the upper film of the water bag and the glazing of the shallow solar pond does not significantly improve the performance of the pond.

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